Studies in Extracorporeal Circulation. I. Applicability of Gibbon-Type Pump-Oxygenator to Human Intracardiac Surgery: 40 Cases *

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BASIC laboratory studies on the extracorporeal circulation and oxygenation of blood began many years ago. In 1939, Gibbon [11] reported his pioneering work with perfusion of the entire body during the temporary functional exclusion of the heart and lungs from the remainder of the circulation. Since then, investigative work has progressed along many lines, one of which has been directed toward the development of various types of oxygenators. In general, the methods have followed principles laid down during the earlier work in the field of perfusion of isolated organs, namely the use of biologic oxygenators, the introduction of bubbles of oxygen directly into the blood or the creation of thin films of blood in an atmosphere of oxygen.

This last method was employed by Gibbon in the construction of a stationary vertical-screen oxygenator properly known as the "Gibbon-type oxygenator," [22] whereas in the oxygenators developed by Björk, Melrose and Aird, Dennis and associates, and Jongbloed, the film was created by the passage of the blood across a moving surface. The present-day foam or bubble-type oxygenators are associated with the names of Helmsworth and Clark, Clowes, Gollan, Gimbel and Engelberg, and DeWall.

In the field of biologic oxygenators, the use of autogenous lungs has been reported by Dodrill and associates and by Cohen and co-workers, while homologous lungs in an intact donor have been employed by Andreason and Watson and by Warden and associates. Excised homologous lungs have been used by Mustard and Chute, while Campbell recently has described a method of using heterologous lungs.

The feasibility of open intracardiac surgical technics with complete bypass of the heart and lungs in the treatment of congenital heart disease was first established by Gibbon in 1953, when he successfully repaired an atrial septal defect by this method.[22] Later, Lillehei and associates added greatly to the experience in open intracardiac surgery in man, utilizing the technic of controlled cross-circulation; repair of ventricular septal defects [20] and of the tetralogy of Fallot [19] was first accomplished by them. The initial group of eight cases reported from the Mayo Clinic [18] established the reproducibility of accomplishing open cardiotomy in man while the circulation was supported by means of a mechanical pump-oxygenator.

In 1953, construction of a mechanical pump-oxygenator of the Gibbon type was begun in the Section of Engineering of the Mayo Clinic. In this and other aspects of this problem, the co-operation of Dr. J. H. Gibbon and the International Business Machines Corporation was of inestimable

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value. Herein are reported data from clinical use of this apparatus at the clinic in the first 40 patients undergoing open cardiotomy, which use began only after a period of intensive study in the laboratory.[9, 14]

METHODS

The design of the Gibbon-type pump-oxygenator used at the clinic has been described previously.[16] Certain aspects of it and the technic employed in its use are worthy of comment.

Blood from the open chamber of the heart is collected continuously through a specially constructed sucker and returned under low vacuum to the pump-oxygenator along with the systemic venous return. In the 40 cases reported, 20 to 30 per cent and occasionally more of the venous return from the patient was from the open heart and the amount of flow through this intracardiac sucker system often was as much as 500 ml. per minute. If this blood were discarded, the loss would limit severely the time allowed for work within the opened heart unless impractically large quantities of blood were available. With the present system, a relatively clear operative field is obtained, which is not materially improved by temporarily cross-clamping the ascending aorta to stop coronary flow.

In contrast to the situation in the original Gibbon-type machine, the concentration of carbon dioxide in the oxygenator chamber is not regulated by a pH meter but is kept continuously at 5 per cent or near normal alveolar concentration, while the oxygen concentration is 95 per cent. Mild drifts in pH, when they occur, are treated by the addition of appropriate amounts of a 5 per cent solution of sodium bicarbonate to the blood in the machine. In 21 of the 40 cases comprising this series, sodium bicarbonate has not been added during the perfusion; amounts of sodium bicarbonate averaging about 50 ml. per case have been used in the remaining 19 cases.

The oxygenator is simple in principle and

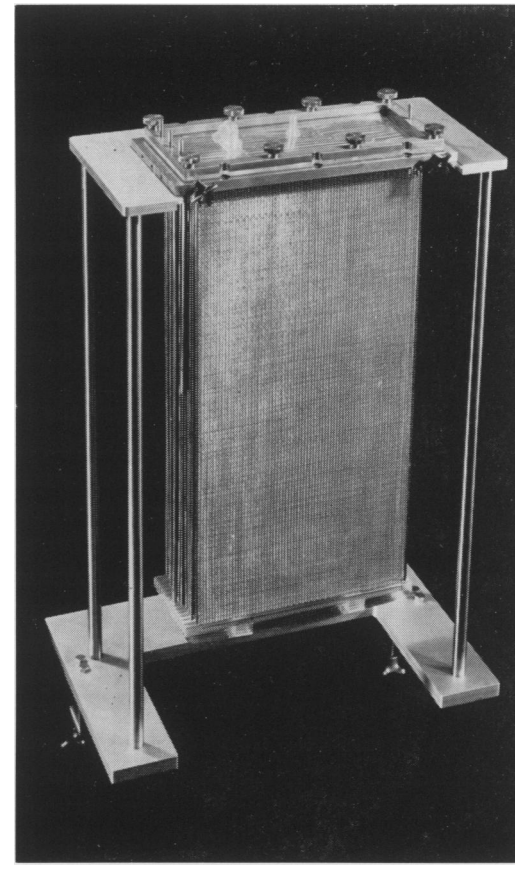

FIG. 1. Stationary screens of the Gibbon-type oxygenator.

operation. There are no moving parts and neither air nor oxygen is bubbled through the blood. The blood flows evenly and smoothly down the vertical screens on which respiratory exchange occurs (see Fig. 1) and collects in the arterial reservoir at the bottom of the oxygenator casing ready to be pumped back to the patient.

The pump-oxygenator is rendered a precision instrument by the incorporation in it of previously described automatic controls.[16] As a result of the interaction of these controls, the volume of blood within the pump-oxygenator is maintained at a constant amount and the blood returned to the patient is quantitatively equal to that leaving the patient to go to the unit. This is of obvious fundamental importance to safe extracorporeal circulation.

All of the venous return of the patient is utilized in establishing extracorporeal circulation and no attempt is made to restrict flow. This is accomplished easily by this particular pump-oxygenator, since it safely accommodates large flows. In two adult patients, flows of 4,800 ml. per minute have been maintained. It is believed that approximation of normal cardiac output is of value in the optimal maintenance of the patient, which may be of particular importance in critically ill persons or in those undergoing long periods of open cardiotomy. Most of the intracardiac procedures in this series were accomplished in 10 to 25 minutes, but it has been necessary to work within the open heart in some surviving patients for as long as 45 minutes. Technical errors are avoided by having such time available for accurate work. No doubt closely related to the availability of ample time is the fact that there have been no known gross technical errors in the corrective intracardiac procedures as determined either clinically or at necropsy.

The acquisition of suitable apparatus is, of course, essential to the performance of satisfactory extracorporeal circulation. Equally essential are the training and disciplining of a surgical team that is completely familiar with all aspects of this special technic. The surgeon and his assistants, the surgical nurses and the anesthesiologist must all co-ordinate their activities. In addition, the person whose responsibility it is to conduct the extracorporeal circulation also becomes part of the operative team. The recording and interpretation of physiologic data allow precise control of the patient during operation and provide material for later study of a number of variables. Only by the close co-operation of each member of this team can the best results be obtained.

EVALUATION OF APPLICABILITY

The evaluation of the applicability of a pump-oxygenator to the surgical treatment of intracardiac lesions is not easy. Controlled experimentation in the patient is not possible or desirable but data can be collected that aid in this evaluation. Cognizance must be taken of the fact that selection of patients, anesthesia, surgical technic, methods of collecting blood from donors prior to operation and postoperative care are but a few of the myriad of factors influencing most variables by which one would like to study the applicability of the mechanical pump-oxygenator system.

In spite of these limitations, a presentation of such data appears warranted. This may be facilitated by a consideration of three categories, namely, (1) support of the patient during open cardiotomy, (2) extent of undesirable sequelae and (3) mortality rates.

Support of the Patient During Open Cardiotomy. This is judged by continuous observation of (1) the central venous pressure, (2) the oxygen saturation of the mixed venous blood, (3) the rate of blood flow and (4) the pH of the arterial blood returning to the patient. Subsequently, the efficacy of this support is judged by the ability of the heart and lungs to resume their function at the end of the perfusion.

The perfusion has been satisfactorily maintained in every instance for the time required for the intracardiac procedure and in no case has premature termination of the operation been necessary. Although data are as yet incomplete, the impression has been gained that for each patient there is a lower limit in terms of rate of blood flow below which the behavior of the variables just mentioned indicates deterioration in the status of the patient. For example, in patients who weigh less than 10 Kg., perfusion flows of 80 ml. per kilogram of body weight per minute will be accompanied by an oxygen saturation of venous blood of more than 65 per cent, a central venous pressure near normal and stable pH readings; the same situation will pertain in persons who weigh about 50 Kg. with flows of about 50 ml. per kilogram per minute. Dur-

TABLE 1. *Data* During Extracorporeal Circulation in 40 Patients Grouped According to Weight*

Number of Cases	Weight, Kilograms		Perfusion Flow, ml./Kg./min.		Oxygen Saturation of Mixed Venous Blood, Per Cent		Arterial pH	
	Average	Range	Average	Range	Average	Range	Average	Range
6	5.3	3.6–9.0	125	80–200	78	72–84	7.34	7.23–7.44
15	15.7	13.2–19.1	78	54–125	68	59–84	7.27	7.24–7.34
12	23.2	20.5–30.0	74	24–125	67	42–83	7.31	7.20–7.45
7	52	49–66	52	20–91	67	43–82	7.34	7.24–7.42

* Figures are averages of values recorded throughout the individual perfusions.

ing perfusion, the arterial pressure, central venous pressure, oxygen saturation of the mixed venous blood and pH values usually increase or decrease with the blood flow. The perfusion flow is an extremely sensitive index of the total blood volume within the patient and the machine. Thus, for practical purposes, it is assumed that a decrease in blood flow reflects an unmatched loss of blood from the patient. This fact has been of considerable value in supporting the blood volume of the patient.

Average values in the 40 patients for blood flow, venous oxygen saturation and arterial pH during perfusion are shown in Table 1. The oxygen saturation of blood returned to the arterial system of the patient was 100 per cent in all instances. The oxygen saturation of the mixed venous blood leaving the patient for the machine likewise has been maintained at normal or nearly normal levels in all but two patients in whom it was determined. In these two patients, the flow of blood was less than that usually obtained.

Excessive loss of blood was the causative factor in two of the three patients with flows of less than 40 ml. per kilogram of body weight per minute; mechanical obstruction of one of the lines to the machine was responsible for the decreased flow in the third patient.

In general, the patients who underwent the greatest changes in pH during perfusion were those in whom for one reason or another the perfusions were not completely satisfactory. The average value for all determinations of pH during all perfusions was 7.31.

Mean intra-arterial blood pressures in these patients have been uniformly less than the mean pressures before extracorporeal circulation. Although again the evidence is not complete in this regard, it strongly suggests that blood pressure is of less significance during extracorporeal circulation than is blood flow.

Continuous electro-encephalographic recordings have been made and in no instance have changes of a disturbing nature occurred during the perfusion. Cardiac action has continued throughout the perfusion, and ventricular fibrillation has not been encountered during extracorporeal circulation.

As already indicated, the condition of the patient at the end of the perfusion perhaps is determined best by the ability of the heart and lungs to resume normal function. In the absence of abnormal rhythm, the heart always has taken over the circulation well after perfusion. Only one instance of ventricular fibrillation has occurred after extracorporeal circulation was discontinued. In this patient, it was considered immediately after perfusion that hypovolemia was present; as a consequence, citrated blood unwisely was introduced directly into the aorta. Ventricular fibrillation promptly occurred. It was possible immediately to resume extracorporeal circulation. Normal cardiac rhythm was re-estab-

lished easily and extracorporeal circulation then was discontinued uneventfully. This child recovered and is well.

In a limited number of patients, samples of blood have been removed periodically from the left atrium after extracorporeal circulation while the thorax was being closed. The saturation of this blood with oxygen has been 100 per cent in each instance, giving evidence that the lungs were functioning in a satisfactory manner at that time.

Extent of Undesirable Sequelae. Clinical and experimental experience gives reason for the belief that the problems associated with extracorporeal circulation are not mysterious or qualitatively different from the problems of major intrathoracic surgery in general and are not of such magnitude as to contraindicate the continued use of this technic under proper circumstances.

Studies regarding hemolysis during extracorporeal circulation showed that values of less than 40 mg. of hemoglobin per 100 ml. of plasma were present in 38 of the 40 cases, including those in which perfusion was greatly prolonged. In two patients, values for plasma hemoglobin of 0.8 and 1.5 Gm. per 100 ml., respectively, were obtained at the end of the perfusion. However, analysis proved that even greater levels of plasma hemoglobin were present in the pooled blood before the machine was started. Excessive hemolysis of this nature apparently was related to methods of collection, pooling or preservation of the donor blood and has not been encountered since these two cases, both of which were in the early part of the series. Low levels of hemolysis indicate minimal damage to the blood. Determinations of erythrocytes, leukocytes and platelets have been made; the changes in these counts have not been striking and the data are, therefore, not presented in detail.

In 39 of the 40 patients, excessive bleeding has not occurred after operation. The remaining patient, a 17-year-old girl with the tetralogy of Fallot, died of hemorrhage approximately 12 hours after operation. It was in this case that the most pronounced hemolysis (1.5 Gm. of hemoglobin per 100 ml. of plasma) was present in the pooled blood before the machine was started. It appears fair to conclude that the fatal postoperative bleeding diathesis in this patient was related specifically to what might be termed this transfusion reaction. This conclusion is supported by the afore-mentioned fact that bleeding has not been a problem in the other 39 patients. Extensive vascular pleural adhesions were present in three patients; in spite of this, the loss of blood through the intercostal tubes in the postoperative period was no more than one would have expected after any thoracotomy.

Postoperative cerebral disturbances have not been identified in any of these patients. Anuria has not occurred after this procedure.

Pulmonary complications have been encountered postoperatively in some of these patients. In fact, all four of the deaths that occurred in the group of 21 patients in this series who had ventricular septal defects have resulted from such complications. They may be related in some instances to the severity of the pulmonary pathologic changes accompanying the cardiac defect.

Mortality Rates. At the present time, 40 patients have been operated on at the clinic with the aid of the Gibbon-type pump-oxygenator; 24 of these patients are living, giving a survival rate of 60 per cent. One of the 16 deaths occurred 3 months after operation. By itself, the survival rate is of limited value in an evaluation of the safety of extracorporeal circulation, for it is closely related, among other factors, to the type of cardiac defect present and the extent of the disease. Many of the patients operated on with the assistance of extracorporeal circulation were critically ill infants, children or adults, some of whom were in frank, intractable heart failure.

Nineteen of the patients constituted a heterogeneous group with various types of

severe cardiac disease. In this group, a meaningful interpretation of the relation of extracorporeal circulation to mortality rates cannot be made. Fortunately, the series of 40 cases also included a group in which, anatomically at least, the conditions are reasonably uniform and which can be categorized according to the pressure in the pulmonary artery. This group is comprised of the 21 patients who had ventricular septal defects (Table 2). Although, even in

TABLE 2. *Results of Intracardiac Surgical Repair of Ventricular Septal Defects: 21 Cases*

Result	Cases
Living	17
Dead	4*
Total	21

* Three deaths occurred in the first seven cases; only one death has occurred in the last 14 cases.

these cases factors other than the safety of the extracorporeal circulation enter into the mortality rate, perhaps the mortality figures in the treatment of ventricular septal defects do assist in the evaluation of this technic. Details of all but the last one of these 21 patients are published elsewhere.[10] Suffice it to say that 15 of the 21 patients had severe pulmonary hypertension. The ages of these 21 patients ranged from 3 months to 29 years. All of them survived operation but four died in the postoperative period. The remaining 17 patients are well. It might be emphasized that only one death has occurred in the last 14 of this group of patients. One of the surviving patients is a 29-year-old man who was severely disabled before operation.

SUMMARY

The Gibbon-type pump-oxygenator has been used at the Mayo Clinic to maintain extracorporeal circulation of blood during intracardiac operations on 40 patients. It is concluded that this pump-oxygenator, used under proper circumstances, is a reliable and safe clinical tool in the intracardiac surgical repair of cardiac defects.

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ANNOUNCEMENT

The Publishers of ANNALS OF SURGERY, take pleasure in recording the appointment, on June 4, of Dr. John H. Gibbon, Jr. as head of the department of surgery at Jefferson Medical College. With this post came the honor of being named to the Samuel D. Gross Professor of Surgery Chair. He takes the post and chair left vacant by the death, on December 26, 1955 of Dr. Thomas A. Shallow. Dr. Gibbon has been professor of surgery and director of surgical research at Jefferson since 1946, and has served as chairman of the editorial board of Annals of Surgery since 1946.